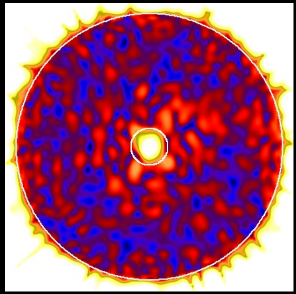
Internal Coronagraph Simulation

John Krist (JPL)

Goal: Create a realistic coronagraphic speckle field

- Speckles are noise against which a planet must be measured
- Wavelength-dependent behavior of speckles
  - Phase vs. amplitude
  - Effects of wavefront control
- Size and shape of speckles
- Time-dependent behavior
  - Changes due to pointing errors, changes in wavefront due to thermal and mechanical stresses
- Requires end-to-end modeling, cannot be directly created

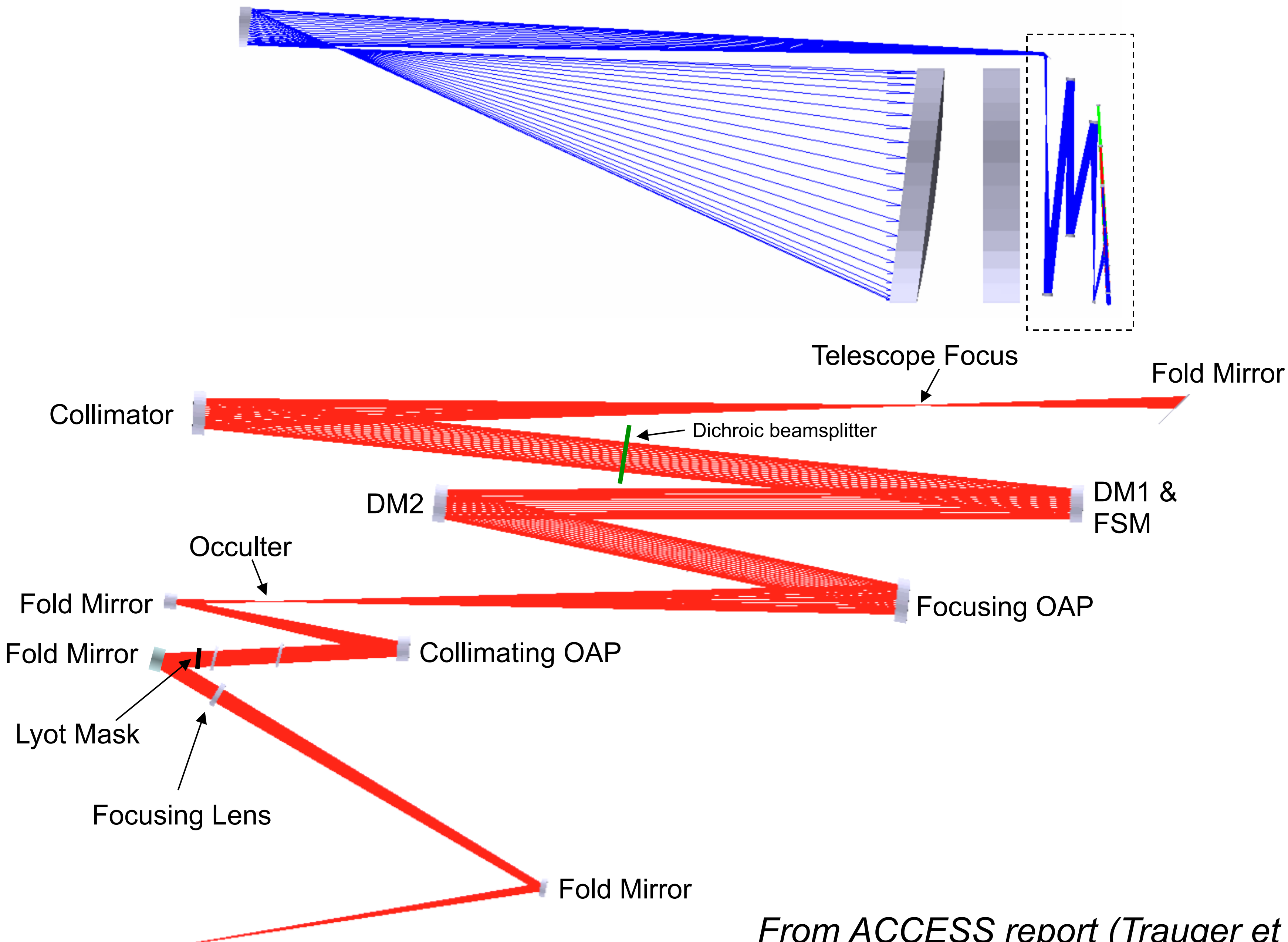


End-to-end modeling to create realistic speckle fields: Requirements

- Model of a coronagraphic system with realistic aberrations and deformable mirrors
- Method of propagating a wavefront between optical surfaces
- Method for sensing of wavefront errors in final image plane
- Method for determining DM settings to minimize scattered light in image plane from optical errors

System layout

- Realistic system layout with all necessary optics
  - For numerical wavefront propagation, system is unfolded into a linear layout and mirrors replaced by thin lenses
  - Optics have realistic fabrication errors
- Deformable mirrors with realistic actuator influence functions
  - 2 DMs in series provide phase & amplitude control
- Bandlimited Lyot coronagraph with amplitude & phase modulating occulter



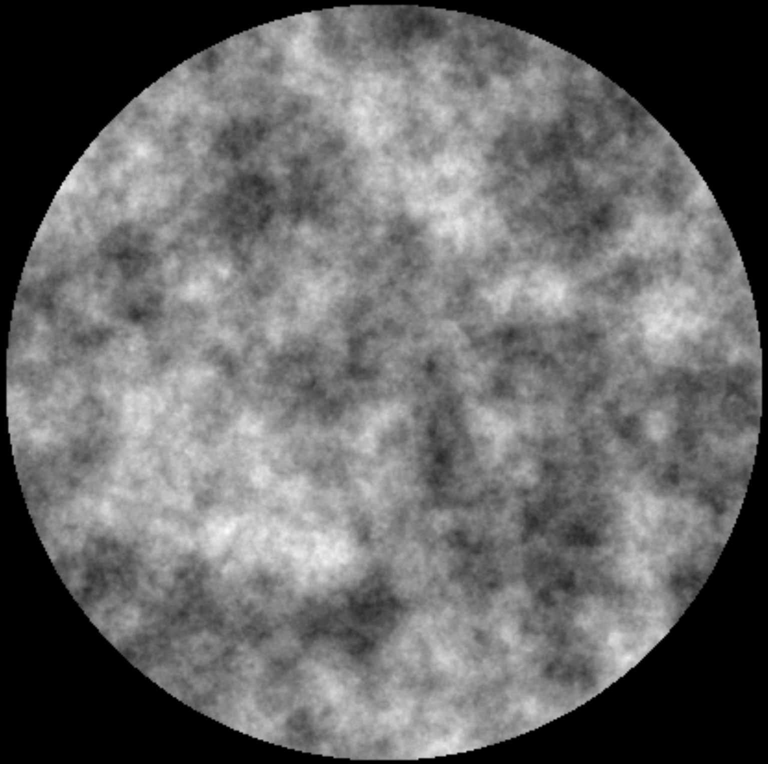
From ACCESS report (Trauger et al.)

Propagation with PROPER

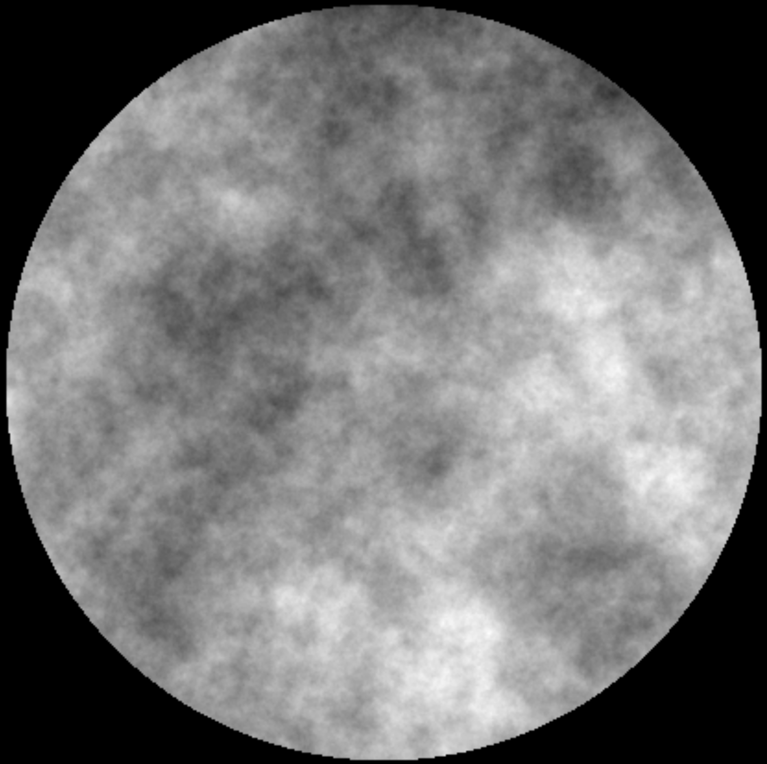
- A freely-available, well-documented propagation library for IDL (*www.openchannelsoftware.com*)
- Fresnel, angular spectrum propagators
- Deformable mirror models with influence functions
- Generates aberration maps from PSD specs
- Also used by Gemini/GPI, VLT/Sphere, Palomar, JWST/NIRCam, JWST/NIRSpec
- NOTE: PROPER does not do wavefront sensing or wavefront optimization; use separate routines

Errors on Optics

Phase Errors
(Figuring, polishing)

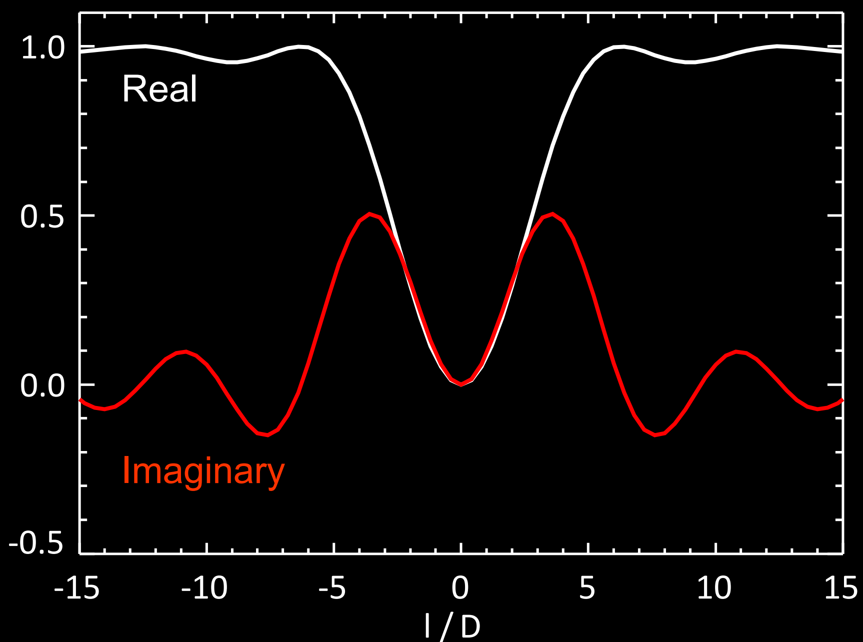


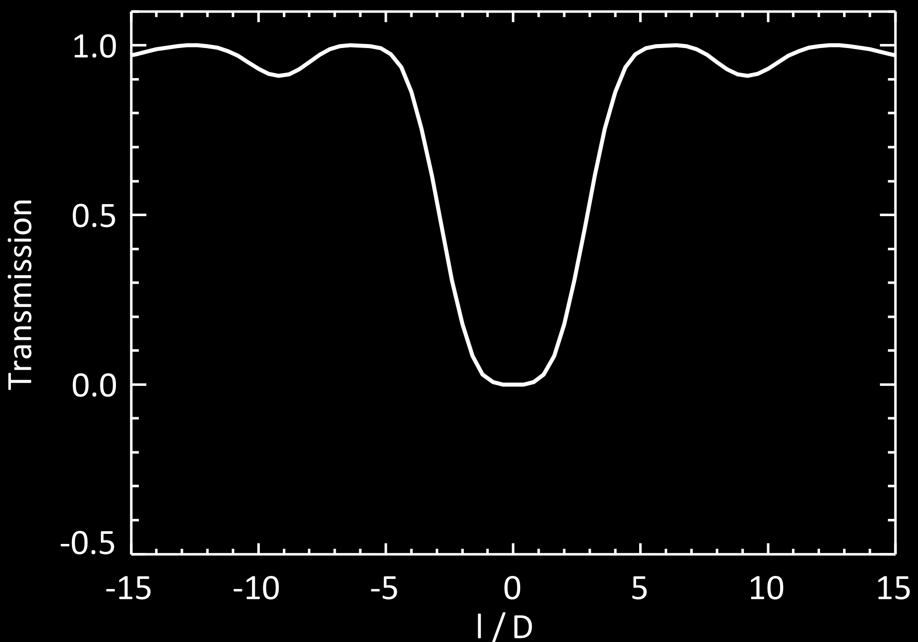
Amplitude Errors
(Coating)



Complex BLC Occulter

Inner working angle (50% transmission) at 3 λ/D @ λ = 550 nm
4th order aberration response

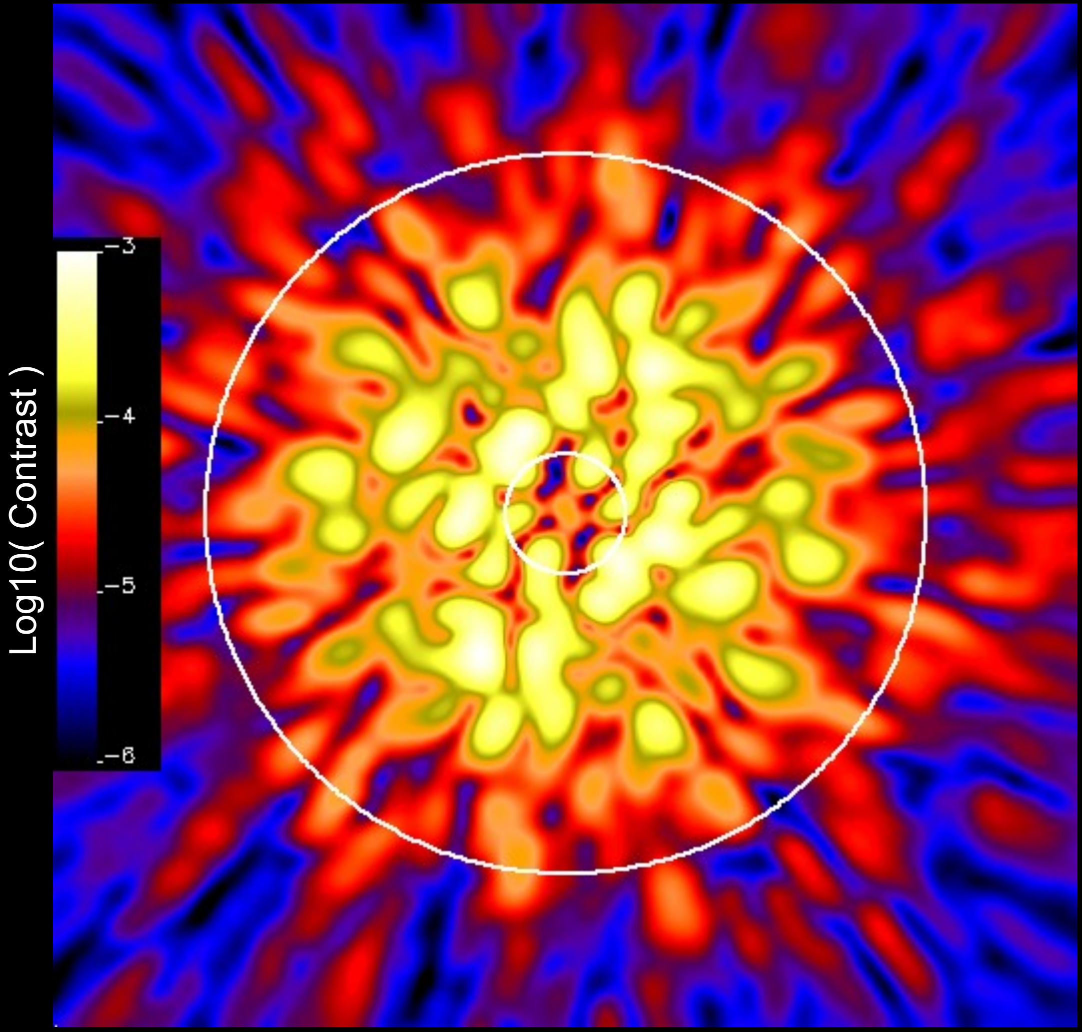




Complex-valued transmission achieved using amplitude-attenuating metal (e.g. nickel) and patterned dielectric coatings (Moody & Trauger)

Contrast before wavefront correction

λ = 500 – 600 nm



Wavefront control:

Electric field conjugation (energy minimization)

Linear approximation to a non-linear system

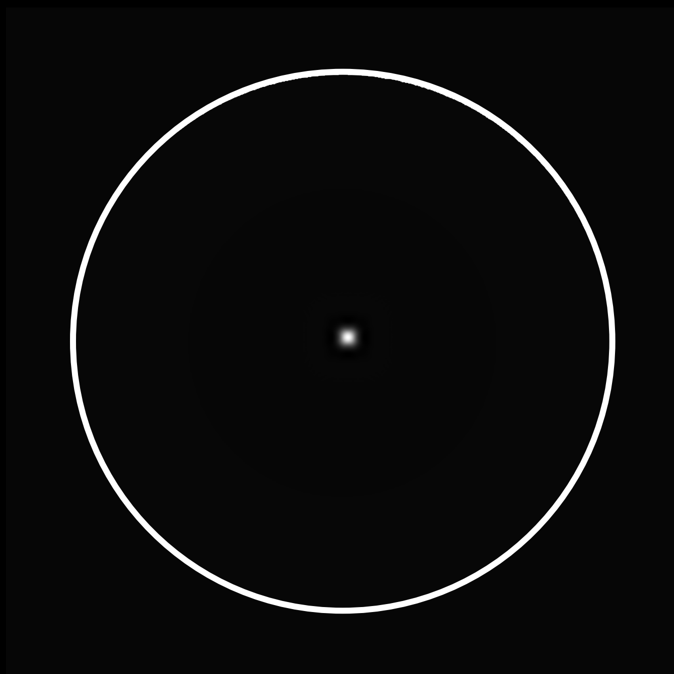
$$\begin{pmatrix} \text{Field change at} \\ \text{image plane } (x,y,\lambda) \\ \text{for each DM actuator} \\ (x_{dm},\, y_{dm}) \text{ poke of } \Delta \text{ nm} \end{pmatrix} \begin{pmatrix} \text{DM actuator} \\ \text{pokes} \\ \delta(x_{dm},\, y_{dm}) \text{ nm} \end{pmatrix} = \begin{pmatrix} \Delta\text{Field at} \\ \text{image plane} \\ (x,y,\lambda) \end{pmatrix}$$

Determined by numerically propagating
DM actuator pokes through a model system

λ = a few wavelengths that sample the bandpass

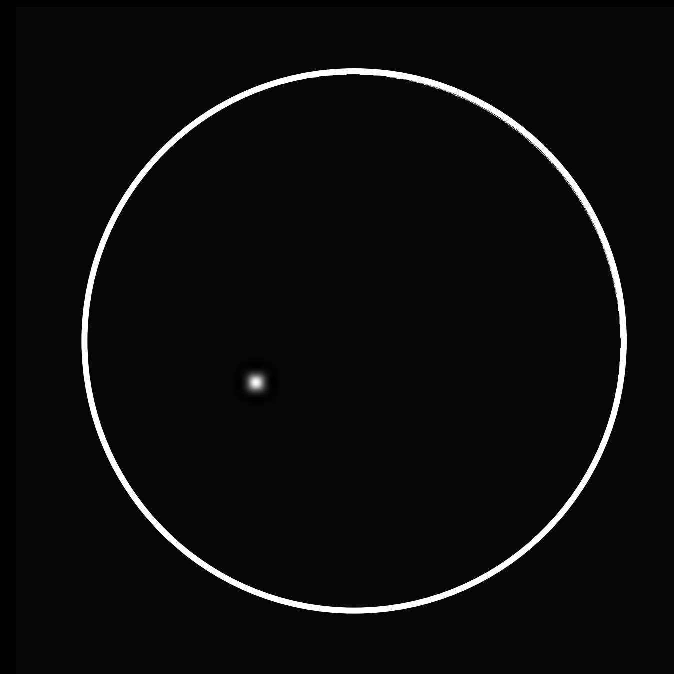
See papers by Give’on and Bordé & Traub

Field changes at final image due to DM actuator piston

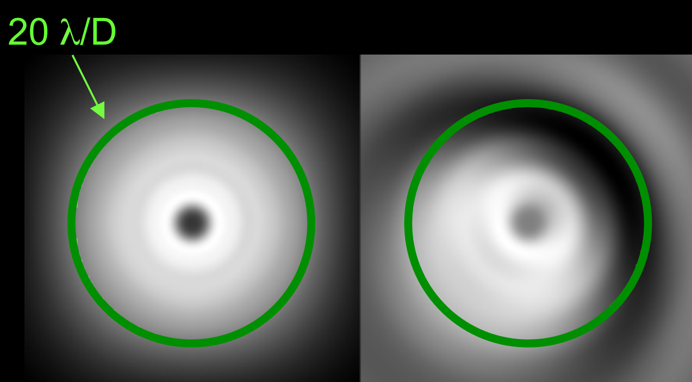


(24,24)

δPhase at
DM #1



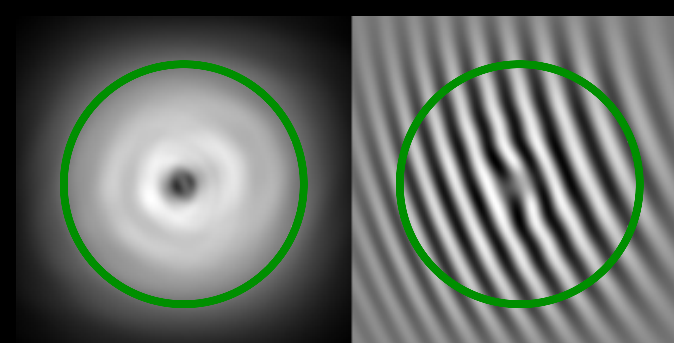
(15,20)



Amplitude

Phase

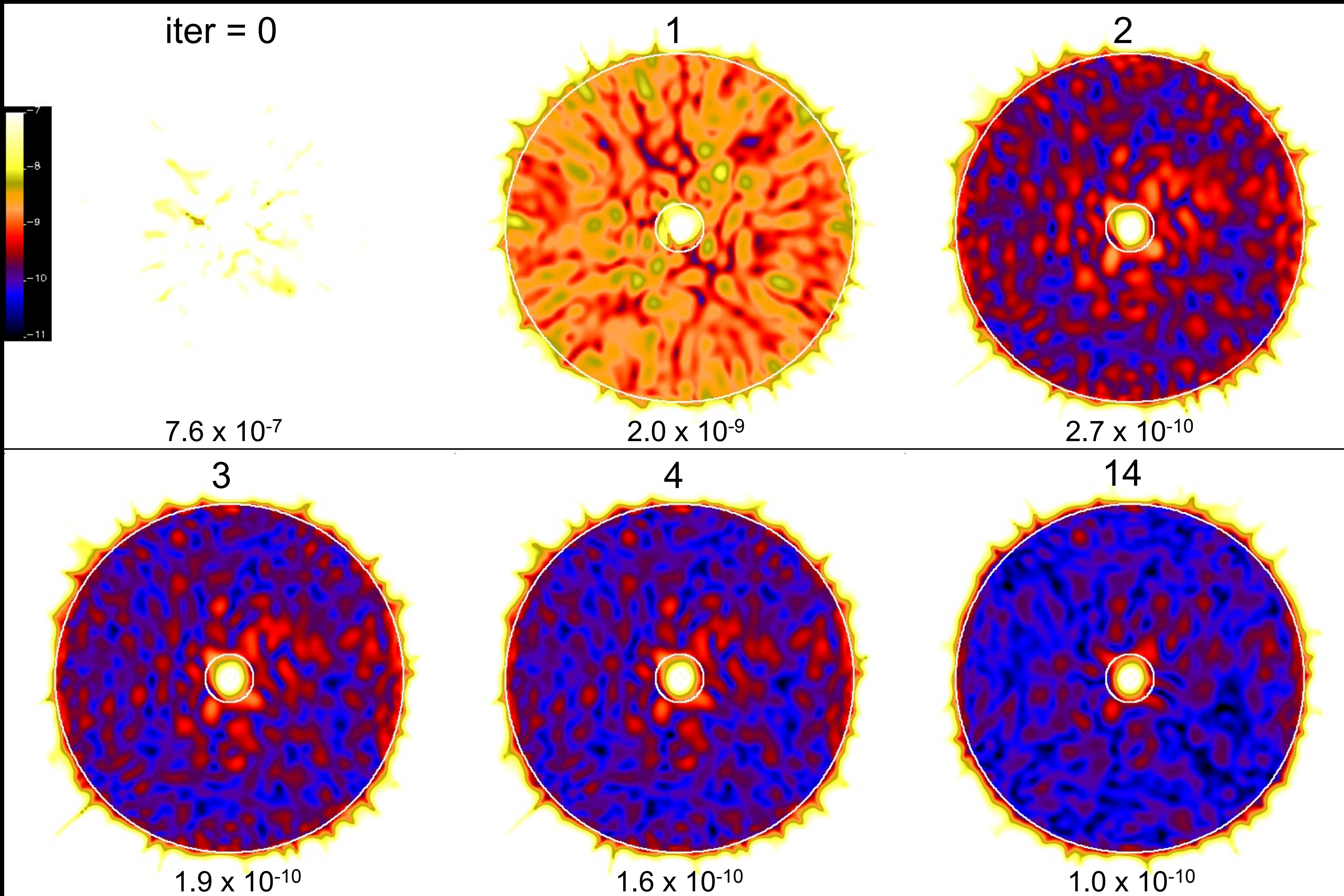
ΔField at
final image



Amplitude

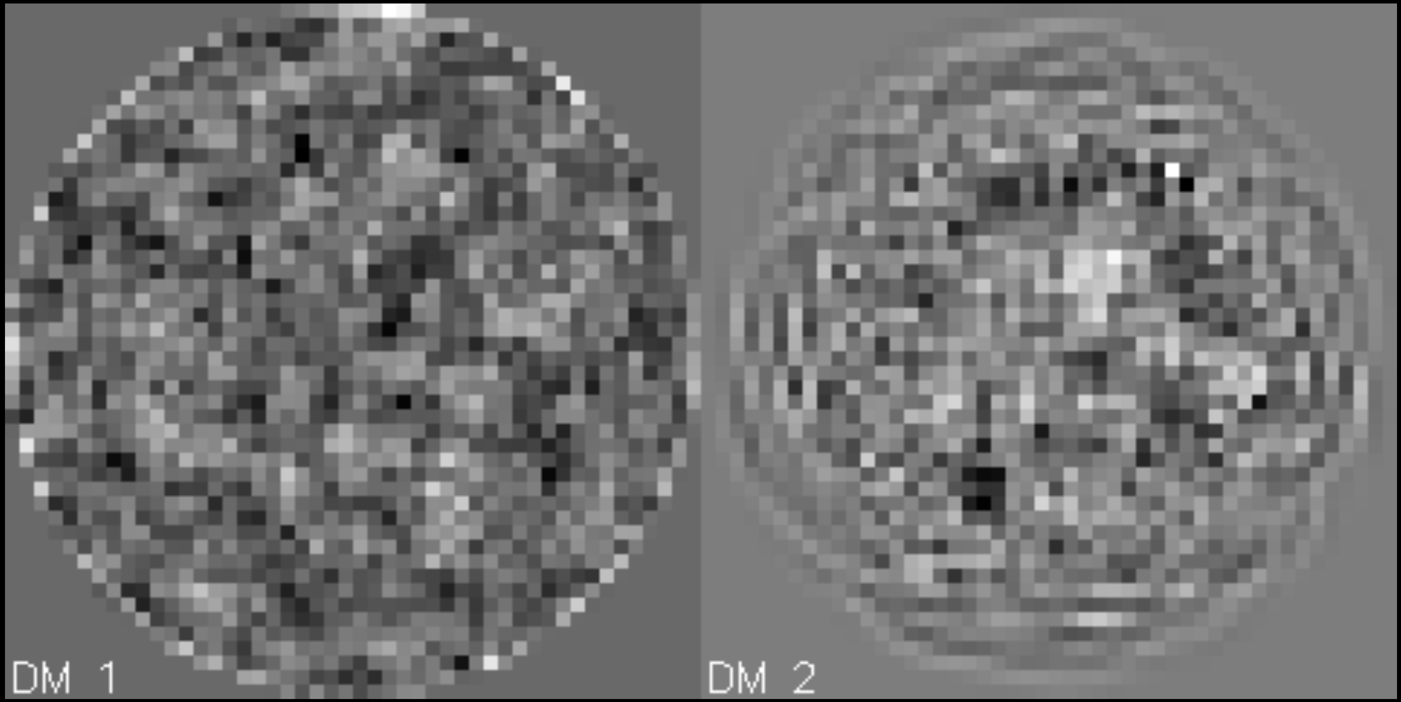
Phase

Iterative wavefront optimization



Optimized DM patterns

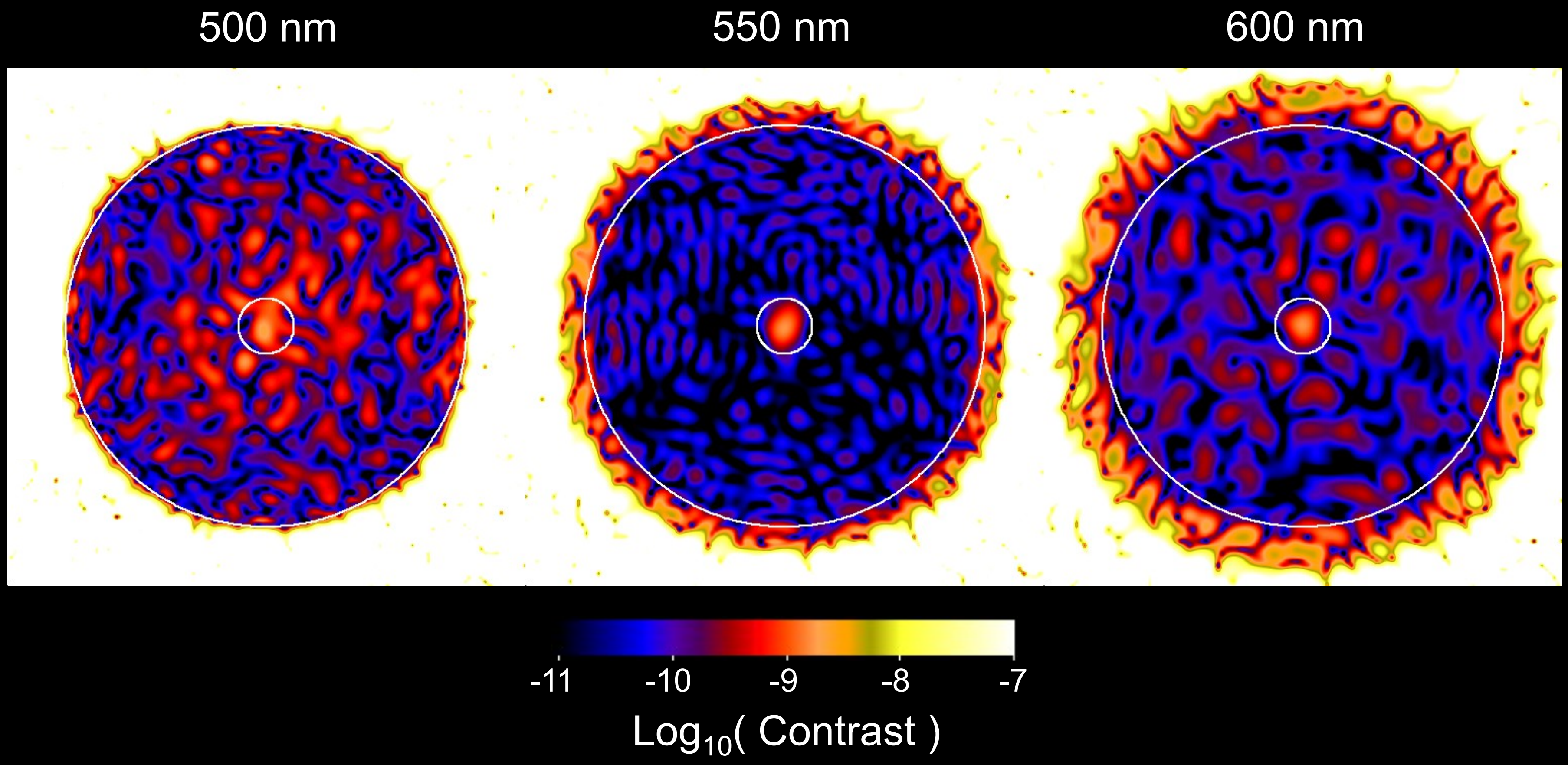
48 x 48 DMs



-23 to +33 nm

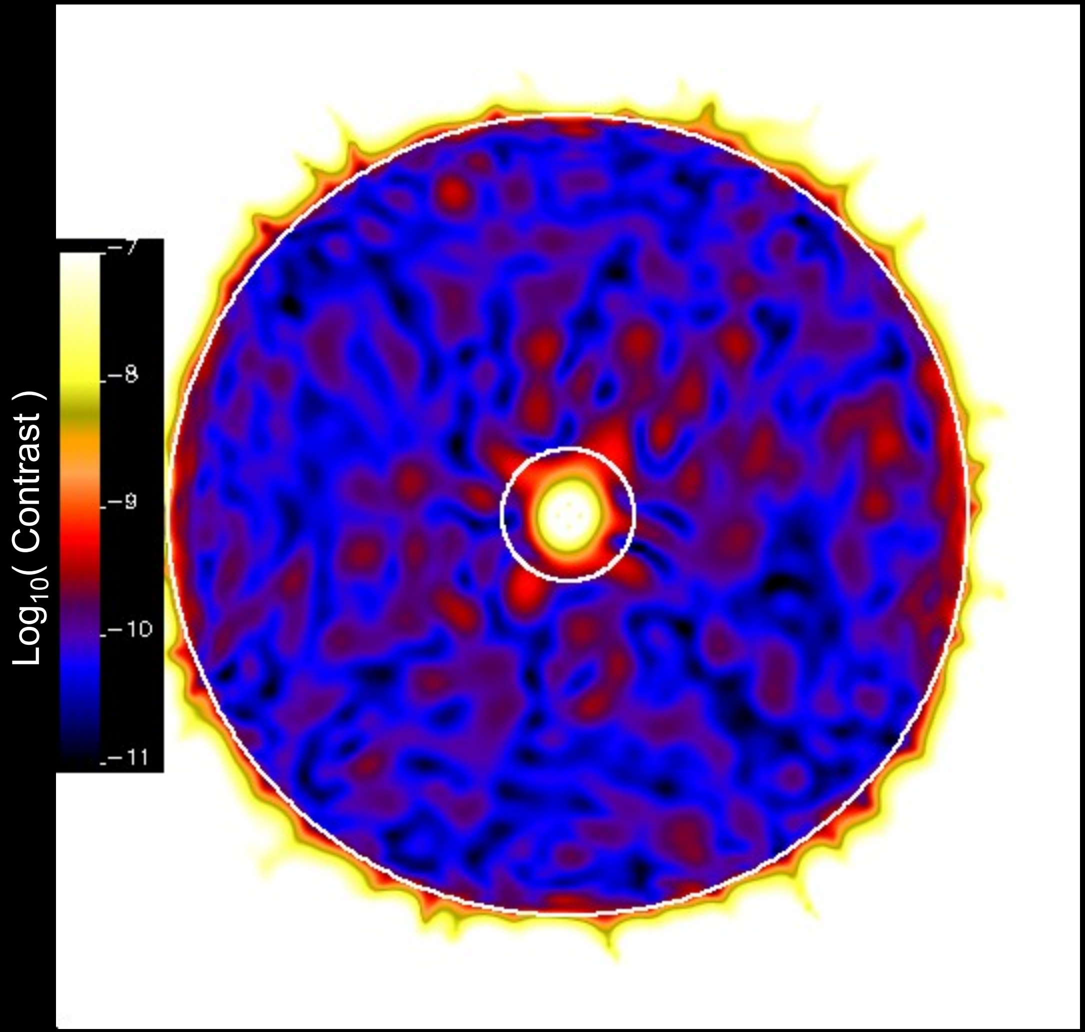
-5 to +5 nm

Dark hole contrast vs. wavelength



Broadband dark hole contrast

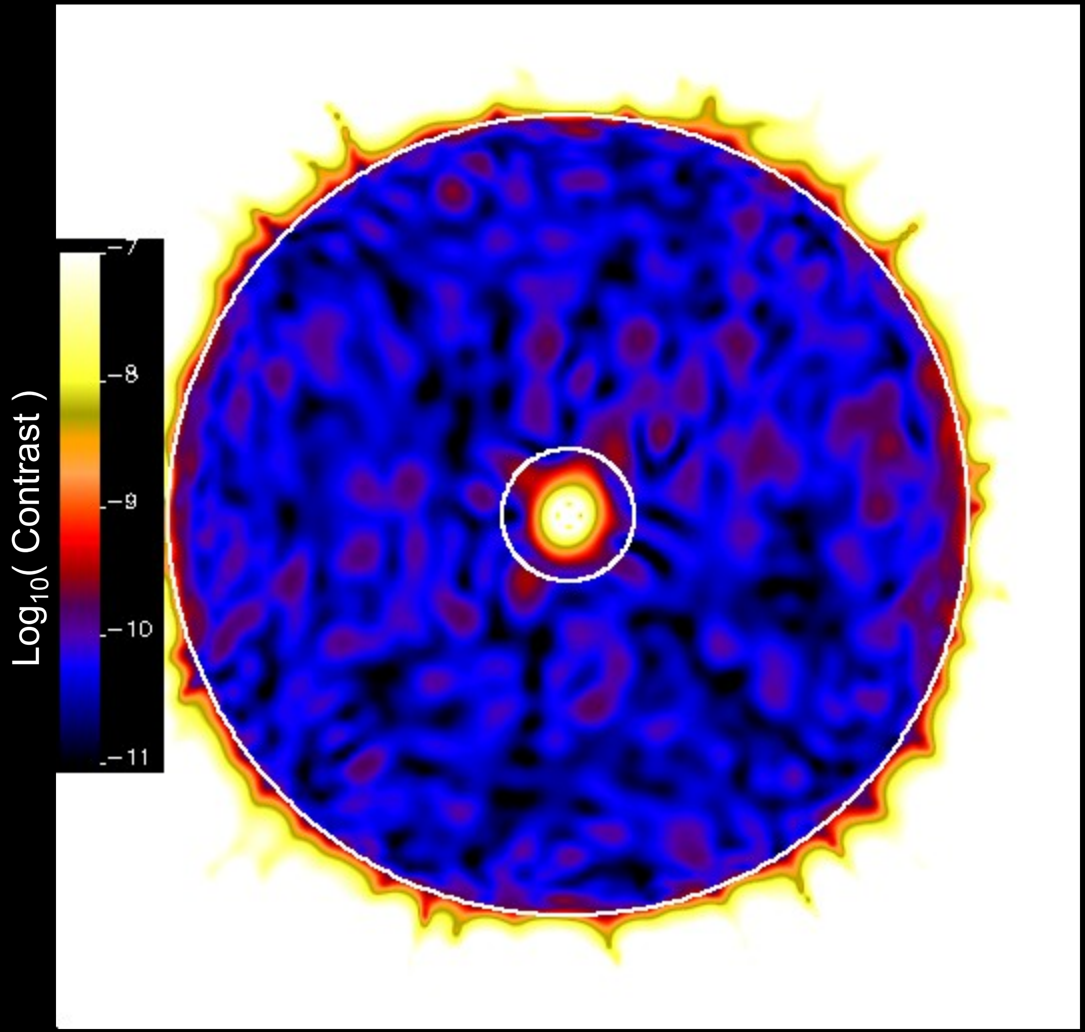
λ = 500 – 600 nm



Mean dark hole contrast = 1.0 x 10^{-10}

Broadband dark hole contrast

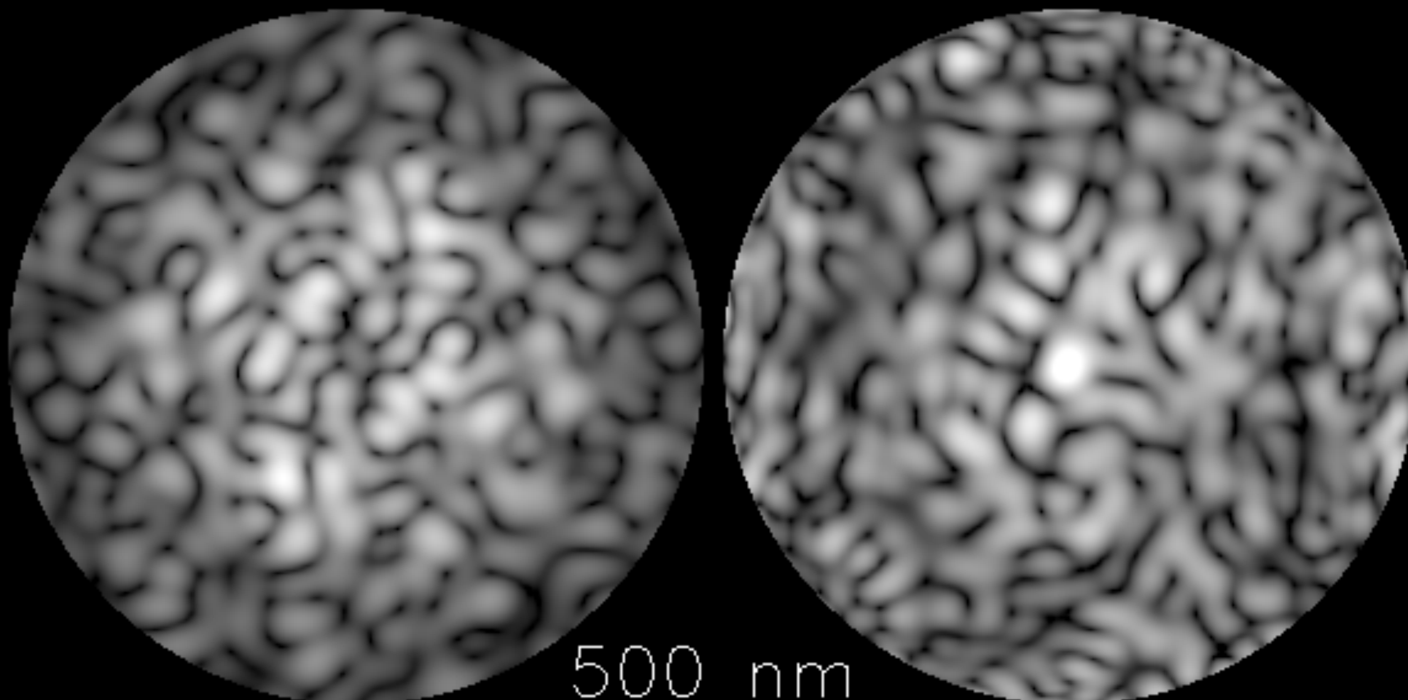
λ = 630 - 770 nm



Mean dark hole contrast = 5 x 10^{-11}

Speckle changes with wavelength

Before Wavefront Correction — After Wavefront Correction



Mean contrast = $1x10^{-5}$ - $4x10^{-4}$

Mean contrast = $3x10^{-11}$ - $4x10^{-10}$

Note: 6 orders of magnitude difference in display intensity scaling

NOTE: Figure animated only when in slide show mode in Powerpoint

Wavefront after 30° roll

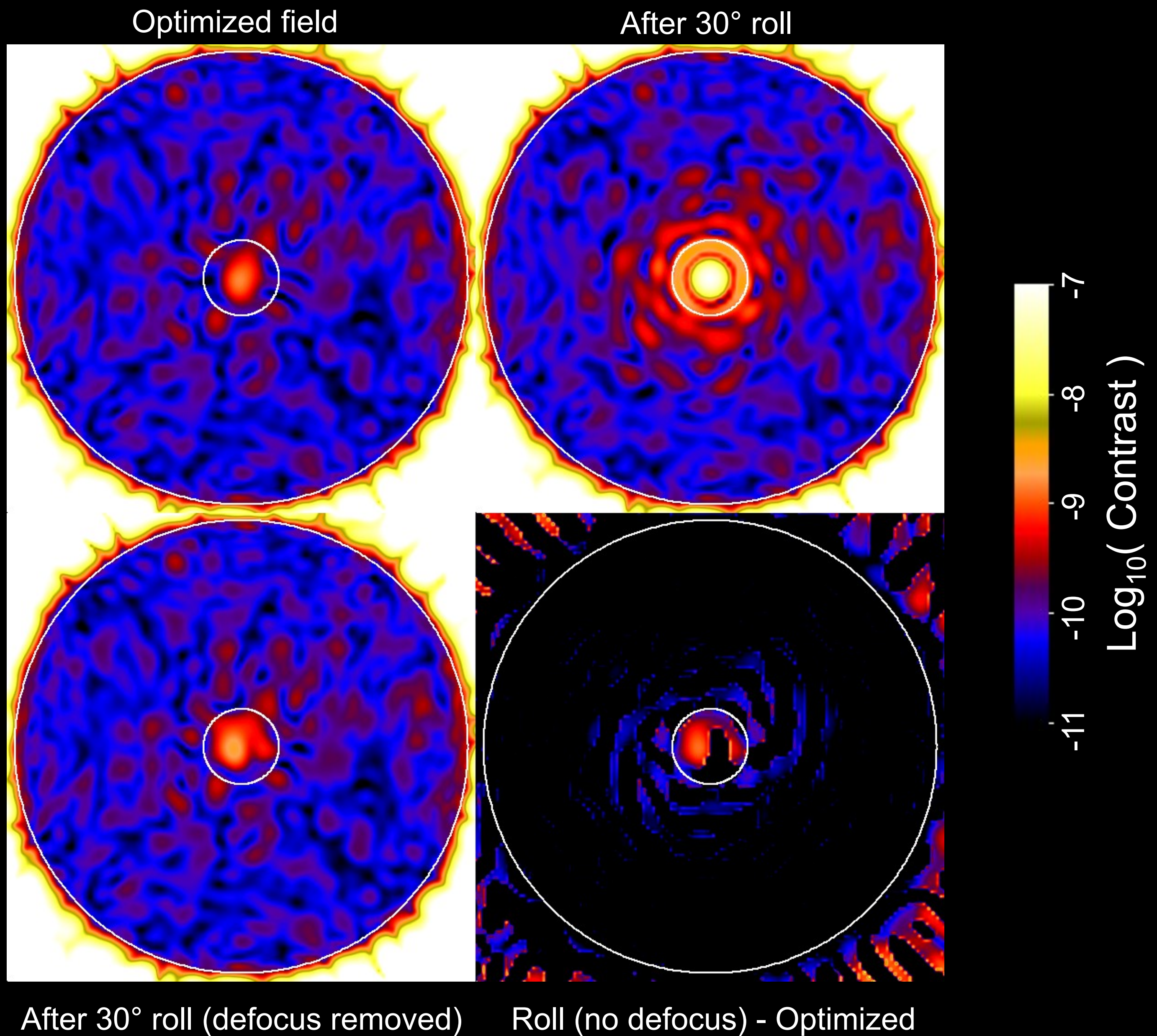
Steady state

Shown with defocus removed

Defocus = 1.5 Å RMS, other = 0.19 Å RMS

From ACCESS study (Trauger et al.)

Dark hole contrast after telescope roll (λ=500-600 nm)



Some important effects not included

- Results shown so far are *instantaneous*
- Wavelength dispersion & induced phase changes
- Manufacturing defects
  - Coating irregularities, dielectric pattern misalignment
- Polarization
  - For 10^{-10} contrast, separate polarization channels required for VVC, perhaps HBLC, probably PIAA
- Off-axis effects
- Time-dependent variations
  - thermal, pointing, structural stresses
- Wavefront sensing
  - Noise
  - Sensing interval
  - Separate low-order wavefront sensing?
- Imperfect DM actuator behavior

Internal Coronagraph Modeling ROSES/TDEM

- End-to-end modeling of HBLC, PIAA, vector vortex
- Accuracy-verified propagators (Milestone #1)
- Realistic system like the one used here
- Propagators for each (interfaces with PROPER routines) will be freely available by early 2012